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Dr. Mark Kirk
US NRC
Office of Nuclear Reactor Research
MEB Branch
Washington DC

Subject: Initial Impressions from Review of ORNL Davis-Besse Vessel Clad Integrity Program

Dear Dr. Kirk:

On December 10, 2003, an all-day review was presented by ORNL and NRC staff on the efforts conducted at ORNL that involved their evaluation of the Davis-Besse RPV head structural integrity. Dr. William Shack, Dr. James Joyce and I were selected by the NRC to be the independent Review Panel members. You had asked us to supply you with a letter summarizing our initial impressions, with particular attention to the experimental program. Below are my initial thoughts, which of course are very preliminary at this time. These are my own opinions and not those of the other review panel members.

Experimental Program Comments

(1) I was feeling relatively comfortable with some of the disk-rupture data developed, until at the end of the day it was stated that the thickness of the cladding area was not directly measured, i.e., by using a digital thickness gage. I understand that some dual indicators were used in the machining process, but the direct measurement by something as simple as an ultrasonic thickness gage should have been done before the test, and at various locations after the test.

(2) The surface of the clad material on the OD surface was well machined to a nice smooth surface. However, the clad surface on the ID surface of the cladding was left in the as-fabricated condition. This surface was wavy, and hence leaves some uncertainty of the exact thickness at the crack location. If we are to consider these tests as being more fundamental rather than trying to simulate the Davis-Besse case, then the thickness should be machined on both sides to a constant thickness and measured in several locations, particularly at the surface flaw location.

(3) There was a significant amount of effort in ensuring the tests were safely conducted, but minimal attention to instrumentation on the test itself.

(4) Given the thickness concern (which may or may not be a systematic problem), and lack of instrumentation to date, ***it is suggested that at a minimum one instrumented test be conducted (perhaps with the a/t of 0.1 and the standard 2" crack length)***. The instrumentation should consist of the following;

a. A measurement of the crack-mouth-opening displacement at the center of the surface flaw, and
b. A measurement of crack initiation and crack growth.

Making these measurements at 600F is difficult. My suggestions on how to make these measurements are:

a. Given the temperatures and deformations in the center of the flaw region, perhaps a stereoscopic digital video camera with an articulating borescope tip can be used. I have used such a camera before that Olympus makes, and the images can be captured either as still frames or continuously with video. There are many ways to synchronize the picture/video with the data acquisition system taking the pressure and other measurements. The Olympus software allows very small displacements to be taken in any three directions. The measurements can be made after the test. (This method is frequently used for wear measurements in aircraft engine components.) The tip of the borescope can be articulated to account for the bulging of the center of the flaw. I made a quick call to my past Olympus salesman, and he said they make a cooling sleeve for the borescope cable and tip so that it could even go to 800F. This cooling sleeve is a special order item with them that typically cost $1,100 to $1,500. The camera itself is much more expensive. We could look into places that might rent the cameras if desired.
b. Very small wires could be spot welded to the edges of the center of the crack mouth to make d-c electric potential measurements. This method works well for remote crack growth monitoring at 600F. We routinely used the d-c EP method in most of the NRC pipe fracture programs for tests up to 600F. The wire locations also provide a good video target. By cross-plotting the crack-mouth-opening displacement versus the d-c EP, the pressure at which the crack starts to grow in the experiments can be determined, as well as the crack length at instability. A 50 to 100-amp constant current power supply could be used and the current wires could be attached to the outside of the flange that is integrally connected to the cladding. (For crack growth measurements, there are some surface-crack calibration curves already, or a more precise calibration curve could be determined.)

(5) The displacement measuring system at the center of the dome was a rather elaborate system, due to the lack of high-temperature LVDTs. There are some high-temperature LVDTs available at Battelle-Columbus as leftover items from the past NRC-IPIRG programs. I'm checking on the displacement capability. They may also have some weldable high-temperature strain gages, which are also difficult to obtain anymore.

(6) ***I'm tempted to suggest a second test where the crack length is much shorter, i.e., 3/8 to 1/2 inch, which might be more representative of a continuous length crack in the Davis-Besse cladding.*** This would be the first step in understanding the effect of multiple smaller flaws (see below discussion).

(7) I believe that everyone would like to know more about the actual flaws in the Davis-Besse cladding. The information to date suggests that there are multiple small surface cracks in the exposed cladding area, which may not necessarily be connected. It is not unusual for stress-corrosion cracks to form in clusters or groups. The spacing between the individual cracks could be important in increasing the actual structural integrity of the flawed cladding. To address this several things need to be done.

a. Of primary concern is the documentation of the Davis-Besse clad cracks. You made a rather nice first attempt to map out the length of the cracks on the surface. A surface exam of the remaining pieces would be helpful. Documenting the depths of these cracks at various points would be equally as important. I recently read a technical paper (within the last 2 weeks) where someone had used a stereoscopic high-powered microscope to examines shallow surface cracks, and effectively took a shallow cut across the crack and "shoveled" the material away[1] so as to see the side view of the shallow surface cracks. This enabled the author to document the depth of the cracks at many points along the crack length without having to physically slice the samples into smaller and smaller sections. (Hope I explained this well enough.) I will give you the reference when I find it.

b. ***A multiple small-flaw disk-rupture test at ORNL would be of value to see if the structural integrity of multiple non-linking flaws can be better understood.*** There are some experimental results on multiple flaw interactions as well as analytical models. Many of these multiple flaw interaction analytical models are for elastic loading that is used for subcritical crack growth. There are different considerations for interactions of multiple flaws for plastic loading, most of which are experimentally based. The ASME Boiler and Pressure Vessel Code (Section XI) flaw interaction rules are very conservative for subcritical crack growth, and hence are in the process of being changed. There are on-going efforts to better define the interactions for elastic-plastic failures. ***These efforts should be reviewed prior to designing such experiments.*** I have many of those papers in my files since I am on those committees. Finally, there are different interactions whether the multiple flaws are co-planar or if they are parallel flaws. The amount of spacing between the flaws to determine when they behave as a single flaw needs to be defined in this case for plastic behavior.

(8) Another possible source of systematic error in the experiments is that the flaws in the experiments were put in using an EDM cutter that gives a crack tip that is blunter than the sharper cracks observed from the metallographic sections of the cracks in the Davis-Besse head cladding. The tendency is that for a given material the blunter

[1] This was kind of like a miniature partial boat sample cut.

EDM crack may have a higher effective toughness at crack initiation in the ORNL disk tests from this aspect. After some amount of the crack growth, the J-R curve of an EDM notch specimen and a sharp crack specimen typically blend together. It might be of value to document the notch acuity aspect on the cladding material toughness in simpler lab specimen tests, rather than trying to fatigue sharpen the crack in the disk rupture tests. This trend is going in the wrong direction from explaining the experimental results, i.e., sharper cracks may initiate at a lower failure pressure than in the ORNL disk rupture tests. (There is sharp EDM notch versus fatigue-sharpened notch stainless steel flux weld data at 550F in the PIFRAC database from the NRC piping fracture experiments. I can check on that.)

(9) The ORNL disk-rupture experiments being conducted are at a constant temperature. There is some speculation that the actual Davis-Besse cladding material may have had a temperature gradient through the thickness. This is based on the fact that water after it comes out of the axial crack in the CRDM tube will be at a much lower temperature that could create some boric acid/water pool in the cavity that could be at some lower temperature than the 600F temperature of the RPV head. The RPV head is a very large thermal mass, and the water in the reactor pressure vessel is constantly being reheated to keep the RPV head steel at the high temperature, i.e., there is essentially an infinite heat source of 600F water to heat the steel. I've seen some thermal analyses by Dominion Engineering on the temperature in the cavity from an industry public meeting (May 22, 2002 meeting), but that should be looked at further if this is a concern. The effect of having a lower temperature on the OD surface of the cladding would be to increase the cladding strength and possibly increase the cladding toughness in the Davis-Besse case compared to the 600F isothermal experiments being conducted. Conducting an isothermal experimental at the lower bounding cladding temperature should bracket the cladding behavior. I hesitate to suggest conduct the thermal gradient cladding disk rupture test which would be much more expensive. Rather bounding it and determining the significance of the temperature effects and perhaps analytically accounting for the temperature gradient may be worthwhile.

(10) Another difference between the Davis-Besse case and the ORNL disk rupture tests is the loading conditions. In the ORNL tests, the disk region is loaded only by the pressure normal to the inside cladding face and the edges are clamed. In the Davis-Besse case, the existence of the hole in the head causes the hole to expand due to the hoop stresses in the head. This loading will put a tensile membrane loading all around the cladding (like tightening the cover on a drum). This will stiffen the cladding material and reduce the outward bulging, but increase the pure membrane stresses. I'm not sure how this will change the fracture behavior, but I suggest that Paul Williams at ORNL conduct a sensitivity study on this. From the CRDM work done in 2002, I know Paul has a model of a PVRUF RPV head, where we looked at the effect of pressure loading on the hole opening for CRDM analyses. In our CRDM work, the hole expansion in the RPV head (from pressurizing the whole vessel) caused as much loading on the CRDM tube as the weld residual stresses.

Analytical Program Comments

(1) The finite element model appeared to be refined enough along the edge to properly represent the boundary conditions. Using 20-noded reduced integration elements is the correct approach to simulate the large deformations. I do not remember seeing a FE mesh at the crack tip area, but Paul Williams is usually very diligent in such matters. Putting a small keyhole at the tip is an analytical method to avoid excessive element deformations at the crack tip, which I'm not sure if that was employed. We did not discuss the J path independency aspects or details of that nature.

(2) Care needs to be taken with statistically fitting several parameters to describe a material property such as a stress-strain curve or the J-R curve. The correlations between these parameters should be examined. For instance, the J_{Ic} of the material is strongly correlated to the tearing modulus, and hence should not be independent random variables. Similarly, the yield, ultimate, and strain-hardening exponents of the material are not independent variables. Additionally, the toughness may be related to the strength of the material. There are some statistical fitting results for stainless steel flux weld and relating strength to toughness in NUREG/CR-6004 that may be of interest.

Material Property Investigation

(1) The NRC and ORNL staff expressed concern that constraint conditions are different in the disk-rupture tests than the notched bend-bar specimens. I agree with that, but rather than doing compact-tension (CT) tests that give higher constraint conditions, I'd prefer to see some tests conducted that have notch orientations and loading conditions that look closer to the surface-flawed disk rupture tests. To this end, I'd suggest some fixed-grip single-edge-notched tension (SENT) specimens. These could be made in a similar fashion to the way tensile specimens are cut from the remaining cladding material after a disk-rupture test. We are finding such specimens are much more representative of constraint conditions for surface-cracked pipe. The disk-rupture tests, however, will have much larger loading parallel to the crack than the SENT tests or my past pipe tests. This effect of loads parallel to the crack tip on constraint is a state-of-the art aspect of fracture mechanics, so there is not a clean easy answer on how to define these constraint conditions. Hence, from a detailed disk-rupture test (with constant thickness and well instrumented) the fracture resistance can be calculated with the transverse constraint loading conditions. The general trend, however, with the SENT specimen is that there is lower constraint than a bend-bar or CT specimen, which is in the wrong direction of explaining the results. Only the transverse load effect on the fracture constraint condition may be in the right direction to explain the ORNL disk-rupture results.

(2) There are stainless-steel-flux-weld surface-cracked pipe tests data that might be relevant. In all our past surface-cracked pipe tests, the crack initiation loads were generally very close to the maximum load. A quick look at Experiment 4141-2 from the Degraded Piping Program test on 6" diameter 0.584" thick pipe with a circumferential surface crack with a depth of 64 percent of the thickness (ligament close to the Davis-Besse cladding) in the center of a SAW weld had the crack initiate

within ~3 percent of the maximum longitudinal stress. The SAW weld initiation toughness (in a CT specimen) was 100 kJ/m^2 (561 $in\text{-}lb/in^2$), which is comparable to the stainless steel cladding toughness. The pipe was pressurized to 2,200 psig and loaded in bending to failure. The hoop stress was much lower than the axial stress across the crack (need to look at details further to get the proper biaxial ratio). Hence, I suspect that most of the ductile tearing observed in the ONRL disk-rupture tests occurs very close to maximum load, so that the initiation toughness may be sufficient to predict the failure pressure.

Other Aspects

(1) The ORNL rupture-disk experiments involve pressurization at a rate of about 1 hour to reach the failure pressure (with no sustained hold time). This is comparable to many other past piping fracture tests that I'm aware of. However, there is an effect of sustained loading where at the high stress region near the crack tip can experience primary creep. The Davis-Besse cladding was held at a constant pressure for months. The sustained load failure pressure is lower than the monotonically increasing failure pressure. In carbon steel pipe fracture experiments at room temperature (similar ductile fracture mechanism), the sustained-load failure pressures are typically 5 to 15 percent lower than the monotonically increasing failure pressure. This sustained load effect on lowering the failure pressure happens even at cryogenic temperatures with aluminum vessels. (I have references on this.) This effect would tend to lower the failure pressure predicted by the ORNL disk-rupture experiments and analysis.

(2) In examining the Davis-Besse clad cracks, it appears that the cracks have a residual crack-mouth-opening displacement, but no blunting at the crack tip. Assuming these sections were at the worst-case locations, the Davis-Besse cladding was not at incipient failure conditions. Hence if we can determine the critical CTOD for the clad material under the biaxial loading, then the crack-mouth-opening displacement needed to get to crack initiation could be determined. Since the pressure should be related to the crack-mouth-opening displacement (for a given crack depth and given structural geometry), it should be possible to use the residual CMOD in the metallographic sections to determine the margins from the pressure at crack initiation. Some additional finite element analysis of the type already started at ORNL is needed to come up with the relationship in Equation 1.

$$\text{CMOD} = f(\text{pressure, crack geometry, structural geometry, strain hardening}) \qquad (1)$$

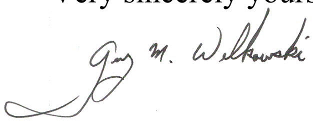
So that for a given material in the same structure and with the same crack we would have,

$$\text{CMOD}_{\text{section}}/\text{CMOD}_{\text{crack-initiation}} = f(\text{pressure}_{\text{Davis-Besse}}/\text{pressure}_{\text{crack initiation}}). \qquad (2)$$

The relationship in Equation (2) could be normalized for any crack length (like the key-curve method Dr. Joyce pioneered) so we may not need to know the crack length to predict the margins to crack initiation for the actual Davis-Besse cladding. Since the pressure at crack initiation is frequently close to the failure pressure for a surface-cracked geometry, this should be a slightly different way of assessing the margins in the Davis-Besse cladding from the residual crack-opening displacement evidence.

Given more time, I can properly organize these thought into which parameters may increase versus decrease the failure pressures from the ORNL experiments relative to the Davis-Besse case, and whether they might be or first, second, or third order effects.

Very sincerely yours,



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